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and the  
GALACTIC TIDAL FIELD**

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## Abstract

The Milky Way is surrounded by nine or more dwarf-spheroidal (dSph) satellite galaxies that appear to consist primarily of dark matter. Here I summarise research that shows that initially spherical bound low-mass satellites without dark matter, that are on orbits within a massive Galactic dark corona, can evolve into remnants that are non-spherical, have a non-isotropic velocity dispersion tensor and are not in virial equilibrium, but are bright enough for sufficiently long times to be mistaken for dark-matter dominated dSph galaxies.

## 1. Introduction

At a distance ranging from a few tens to a few hundred kpc the Galaxy is surrounded by nine or more dSph galaxies which are barely discernible stellar conglomerates, some appearing flattened and having internal substructure. They lie in one or two planes and follow polar orbits around the Milky Way. The stellar content of these is typically similar to that in globular clusters, apart from probably much more complex star formation histories. However, the dSph galaxies are roughly two orders of magnitude more extended (a few hundred pc) and have about the same velocity dispersion (6–10 km/sec) as globular clusters, perhaps implying large quantities of dark matter (e.g. Mateo et al. 1993). If this is true then this would be evidence that dark matter can be a significant contributor to the system mass over length scales of a few hundred pc.

Recent reviews of dSph galaxies are published by Ferguson & Binggeli (1994) and Gallagher & Wyse (1994). Estimates of their structural parameters and a compilation of kinematical data is provided by Irwin & Hatzidimitriou (1995).

One possible alternative to the dark matter hypothesis as an explanation of the large mass-to-light ratio ( $M/L$ , hereafter always in solar units) in dSph galaxies is that these stellar systems may not be in virial equilibrium but instead are significantly perturbed by Galactic tides.

Oh, Lin & Aarseth (1995) model dSph galaxies orbiting in different rigid spherical Galactic potentials. The dSph satellites are represented with  $10^3$  particles using a softened direct  $N$ -body programme. Oh et al. find that while the satellite remains a bound stellar system it would not be mistaken as a dSph satellite with a large observed (i.e. *apparent*) mass-to-light ratio  $(M/L)_{\text{obs}}$ . Given the necessarily relatively small number of particles, the very late stages of disruption and the subsequent evolution is determined but by a few particles and cannot be followed in sufficient detail because two-body relaxation becomes significant. Piatek & Pryor (1995) simulate one perigalactic passage in different rigid spherical Galactic potentials of a representative dSph galaxy, which they model with  $10^4$  particles using the TREECODE. They find that a single perigalactic passage cannot perturb a satellite such that an observer would measure large apparent  $(M/L)_{\text{obs}}$  values.

Thus one would tend to conclude that Galactic tides cannot evolve initially bound satellites with ‘normal’  $M/L \approx 1 - 3$  into dSph-like systems with  $(M/L)_{\text{obs}} > 10$ . Nevertheless, the local dSph galaxies show peculiar correlations between their location relative to the Milky Way and their kinematical, structural and photometric data that appear to bear the expected signature of possibly significant tidal effects (Bellazzini, Fusi Pecci & Ferraro 1996), and Burkert (1996) points out that most of the dSph satellites that lie within a distance of 100 kpc appear to have tidal radii that are too small to permit large quantities of dark matter.

In this summary I discuss the results of two simulations of a representative low-mass satellite that is injected into a massive and extended Galactic dark corona (often referred to as dark halo by other authors) on different orbits. A full report of this work will be available in Kroupa (1997).

## 2. Method

The conventional particle-mesh technique is well suited for the simulation of the dynamical interaction of two galaxies because it is fast and inherently collisionless so that two-body relaxation is negligible. However, the resolution of the central regions of galaxies is limited by the coarseness of the grid.

The simulations described here are performed with a generalisation, by R. Bien and later N. Wassmer, of the conventional particle-mesh technique, making use of the additivity of the potential by employing in total five sub-grids per galaxy. Three of these co-move with the centre of density of a galaxy and the other two contain the local universe. The simulations here use  $32^3$  grid cells in each active grid. An early description of the code, called SUPERBOX, is provided by Bien, Fuchs & Wielen (1991, see also Madejski & Bien 1993).

SUPERBOX computes the radii of the mass shells and the eigenvalues of the moment of inertia and velocity dispersion tensors for each galaxy in the simulation. Every pre-chosen number of integration steps a subset of all particles of a galaxy are stored on disk. These are used to evaluate the projected radial surface brightness profile, the line-of-sight and tangential velocity dispersions and the integrated satellite brightness. Velocity dispersions are estimated using the iterated bi-weight scale estimator (Beers, Flynn & Gebhardt 1990). The central surface brightness, which is obtained from the fitted exponential radial brightness profile, the central line-of-sight velocity dispersion and the half-brightness radius an observer sees from Earth, are used to calculate the *apparent* mass-to-light ratio,  $(M/L)_{\text{obs}}$ , using the King-formula (equation 1 in Piatek & Pryor 1995), the application of which presupposes, among other conditions, sphericity of the stellar system, an isotropic velocity dispersion tensor and dynamical equilibrium.

The Galactic dark corona is represented by a non-singular isothermal density profile with circular speed  $V_c = 220$  km/sec extending to 250 kpc and using  $10^6$  particles, and its nested grids have dimensions of  $(50 \text{ kpc})^3$  and  $(188 \text{ kpc})^3$ . The initial satellite is assumed to be a Plummer sphere, which is as good a description as can reasonably be obtained for a dSph satellite, with a Plummer radius  $R_{\text{pl}} = 0.3$  kpc, total mass  $10^7 M_\odot$  consisting of  $3 \times 10^5$  particles. Each particle is assumed to have a true photometric V-band mass-to-light ratio  $(M/L)_{\text{true}} \leq 3$ . The nested grids have dimensions of  $(1.6 \text{ kpc})^3$  and  $(8 \text{ kpc})^3$ . Both the Galactic dark corona and the satellite are contained in an outer grid with dimension  $(700 \text{ kpc})^3$ , and are individually allowed to relax to equilibrium. An integration time-step of 1.1 Myr is adopted. As a result of the mild contraction the Galactic dark corona becomes slightly prolate. This is a reasonable basis for a model of the dark matter distribution because cosmological structure formation simulations indicate that dark coronae are likely to be non-spherical.

The long-axis of the dark corona is defined to be the x-axis. The satellite is injected 100 kpc from the centre of the dark corona along the x-axis with a velocity vector parallel to the y-axis with a speed of 100 km/sec and 125 km/sec, giving eccentricities 0.74 (simulation ‘RS1-4’) and 0.60 (simulation ‘RS1-5’), and maximum speed near perigalacticon of about 480 km/sec (RS1-4) and 450 km/sec (RS1-5). The orbital period is approximately 2.1 Gyr in both cases.

## 4. Results

Dynamical friction does not affect the orbit owing to the small satellite mass. The satellite loses 10-20 per cent of its particles each time it passes perigalacticon, and the time-varying Galactic tidal field stimulates internal collective oscillations (compare with Kuhn & Miller 1989). The central surface brightness increases temporarily during each perigalactic passage with subsequent reduction due to mass loss, the satellite re-adjusting its structure to new virial equilibrium. During each perigalactic passage the velocity dispersions increase temporarily (compare with Piatek & Pryor 1995). However, as already stressed by Oh et al. (1995), the velocity dispersions show an overall decrease as mass is lost and while the satellite remains bound and in dynamical equilibrium.

After passage through perigalacticon at about 4.6 Gyr (RS1-4) and 6.8 Gyr (RS1-5) the satellite can be considered disrupted, although a remnant remains (compare with Johnston, Spergel & Hernquist 1995)

with half-light radius of a few hundred pc. The central surface luminosity of the remnant decays by a factor of about 100 during the following 3-4 Gyr, with an initial rapid decline that levels off. If  $(M/L)_{\text{true}} < 3$  then the remnants are bright enough for many orbits to compare favourably with the observed dSph satellites.

After disruption near 4.6 Gyr (RS1-4) and 6.8 Gyr (RS1-5) the measured central line-of-sight velocity dispersion of the remnant varies significantly in the range of about 2 to 30 km/sec depending on orbital eccentricity and phase. The velocity dispersion along the orbit is significantly reduced compared to the velocity dispersion along the line joining the Galactic centre and the satellite. This means that the remnant can survive as a distinct density enhancement for long periods (compare with Kuhn 1993). The remnant is non-spherical but need not appear elongated along the orbital path.

Given the structure and line-of-sight kinematics of the remnant viewed in the observational plane, an observer deduces apparent  $(M/L)_{\text{obs}} > 10$ , with values as large as a few hundred, although  $(M/L)_{\text{true}} \leq 3$ .

The plane of both satellite orbits tilts by about the same amount under the action of the torques from the prolate Galactic corona and the transfer of energy and angular momentum. The orbits become increasingly polar but the two orbits remain approximately co-planar.

## 5. Conclusions

Fully self-consistent simulations of the interaction of dwarf satellite galaxies without dark matter with an extended Galactic dark corona indicate that the high  $M/L$  values inferred for dSph satellites do not necessarily imply that these contain dark matter. Rather, high apparent  $(M/L)_{\text{obs}}$  values result naturally from preferential orbital-phase modulated tidal removal of satellite particles leading to highly non-uniform phase space distribution of particles in the long-lived remnant.

The reason for large  $(M/L)_{\text{obs}}$  is that the model remnants have non-isotropic velocity dispersions, are non-spherical and are not in dynamical equilibrium, and may perhaps best be described as amorphous lumps of stars.

The present model prolate Galactic dark corona leads to a roughly planar distribution of remnants on near-polar orbits that bear tantalizingly close resemblance to the observed dSph satellites.

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